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Using MaxEnt modeling to predict the potential distribution of the endemic plant *Rosa arabica* Crép. in Egypt

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ABSTRACT

Climate change poses negative impacts on plant species, particularly for those of restricted ecology and distribution range. *Rosa arabica* Crép., an exclusive endemic species to Saint Catherine Protectorate in Egypt, has severely declined and become critically endangered in the last years. In this paper, we applied the maximum-entropy algorithm (MaxEnt) to predict the current and future potential distribution of this species in order to provide a basis for its protection and conservation. In total, 32 field-based occurrence points and 22 environmental variables (19 bioclimatic and three topographic) were used to model the potential distribution area under current and two future representative concentration pathways (RCP2.6 and RCP8.5) for the years 2050 and 2070. Annual temperature, annual precipitation and elevation were the key factors for the distribution of *R. arabica*. The response curves showed that this species prefers habitats with an annual temperature of 8.05–15.4 °C, annual precipitation of 36 to 120 mm and elevation range of 1571 to 2273 m a.s.l. Most of the potential current suitable conditions were located at the middle northern region of Saint Catherine. Prediction models under two future climate change scenarios displayed habitat range shifts through the disappearance of *R. arabica* in sites below 1500 m a.s.l., an altitudinal range contraction at 1500–2000 m and possible expansions towards higher elevation sites (2000–2500 m a.s.l.). Our findings can be used to define the high priority areas for reintroduction or for protection against the expected climate change impacts and future modifications.

1. Introduction

The ecological niche of a species is the interaction of space and conditions where it is able to survive, persist and continuing its reproductive ability to remain in viable populations (Choudhury et al., 2016). Ecological niches play a central role in explanations of species origin, persistence, distribution and capacity of competition (Silvertown, 2004). Climate, soil features, topography, land-use and biological interactions have been recognized as the main drivers for distribution and ecological niche of species at various geographical scales (Abolmaali et al., 2018; Woodward, 1987). In particular, the climate warming may result in shifts in natural species range specifically for those of geographically limited and/or endemic species which are unable to adapt to unusual climatic conditions and thus become endangered or even extinct (Cuena-Lombraña et al., 2018; Loarie et al., 2008; Parmesan, 2006). Furthermore, human impacts cause additional habitat fragmentation and threaten plant diversity (Tilman and Lehman, 2001; Vásquez et al., 2015). The growing effect of such kind of impacts on plant species calls a request to realize areas where endangered species or species with narrow niche width exist or likely exist in order to enhance their conservation and restoration (Dubuis et al., 2011; Kaky and Gilbert, 2016).

Many endemic taxa are included in the IUCN Red List of the threatened species as they are in danger of global extinction because of their narrow geographic distribution and extremely habitat-restricted (Crisp et al., 2001; Orsenigo et al., 2018). Hence, protecting and conserving such species is important, through addressing the potential distribution of suitable habitats and finding the environmental factors which drive the presence and persistence under current and future conditions (Attorre et al., 2018; Brooks et al., 2002; Primack, 2006). The first step to initiate conservation processes for these taxa is to identify the current geographic distribution, population status and threats that expose them to the risk of extinction (Crisp et al., 2001).

To our knowledge, no previous studies have been done to address

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the ecological niche of *Rosa arabica* Crép. (*R. arabica* hereafter); accordingly, predicting its habitat suitability, in order to estimate its spatial geographic distribution, and exploring suitable persistence conditions are critical to conserving this plant species. Ecological niche models or species distribution models (SDMs) are aimed at predicting the suitable key sites for a target species in relation to environmental conditions where the species is present (Guisan and Zimmermann, 2000). Recently, SDMs are used to reintroduce, manage or rehabilitate numerous threatened species from being extinct in their historical native sites (e.g. Fois et al., 2016; Yang et al., 2013). Furthermore, SDMs can guide conservationist through predicting the impact of climate warming, land use change, exploring unsuitable areas as well as suitable areas with high presence for further surveys, reintroduction or natural preservation of such kind of endangered species (Amici et al., 2017; Fois et al., 2016; Safaei et al., 2018; Thomas et al., 2004). The main task of SDMs is to understand how the environment shapes the distribution of a species in its native area. To do so, we construct a SDM by collecting presence data and environmental features (climate and topography) stored in a geographic information system. Numerical outputs of statistical SDMs have often been simplified to environmental suitability indexes, ranging from 0 (unsuitable) to 1 (optimal). Furthermore, it was proved that such index is often related not only to the probability of occurrence but also to other key parameters of populations, such as growth rate, surface area and number of vegetative and reproductive individuals (Csergő et al., 2017; Fois et al., 2018c).

Among SDMs algorithms, MaxEnt was chosen because of its numerous advantages including: (1) the input species data can be presence points only, (2) both categorical and continuous environmental layers can be applied, (3) its prediction is stable and reliable with a great accuracy even if low sample sizes are undertaken, thus can predict distribution of threatened species, (4) it creates a spatially explicit map for habitat suitability with an easy interpretation, (5) it enables replicated runs to test model robustness nonetheless threshold rule, (6) the importance of each environmental variable can be measured using jackknife test, (7) MaxEnt model (bioclimatic envelope model) can be used to project into the future under climate change to predict habitat losses and gains within species range and thus help in planning appropriate conservation measures (e.g. Elith et al., 2011; Fois et al., 2018b; Pearson et al., 2007; Phillips et al., 2006).

In this study, we addressed the following question: should future climate changes further reduce the suitable habitats for *R. arabica*? If so, this should be considered when planning to protect, restore or reintroduce this plant in its native environment in case of human threats (grazing and cutting) are controlled. Accordingly, we analyzed the potential distribution of *R. arabica* and the possible impact of climate warming. Hence, our objectives were: (1) to predict the current potential distribution, (2) to identify the key environmental factors that highly correlated with *R. arabica* distribution range, and (3) to forecast the impact of projected climate change under two global greenhouse emission hypotheses for the 21st century.

2. Materials and methods

2.1. Study area and target species

Our study was carried out in Saint Catherine Protectorate, which is located in southern Sinai at the northeastern corner of Egypt with a total area of *ca.* 5196 km^2 (Fig. 1a). Saint Catherine is an igneous massif characterized by smooth faced-outcrops that formed mountain areas with an elevation range up to 2640 m a.s.l. (Moustafa and Klopatek, 1995). The location of St. Catherine support the differentiation of distinctive environments (gorges, slopes, terraces, caves and ridges), each of them hosts peculiar plant communities (Moustafa et al., 2001, 2017). Saint Catherine is distinguished by a wide range of variation in air temperature and precipitation. It is categorized as the coolest region in Egypt and the only one that has snow (Moustafa et al., 2017). The average monthly temperatures range from 8.6 °C in January to 25.5 °C in August. The average annual rainfall for 1970 to 2017 was scanty, irregular and was 37.5 mm, but unpredictable one-day flash floods have occurred and reached c. 300 mm (years 2012 and 2014) (Moustafa et al., 2017; Omar et al., 2017).

According to Abdelaal et al. (2018), St. Catherine harbors 14 exclusive vascular plants, and it is therefore considered one of the most important Egypt's protected landscape. The long-term drought, overgrazing and tourism activities are the main threatening factors for the plant diversity in St. Catherine (Grainger and Gilbert, 2008; Moustafa et al., 2001; Zaghloul et al., 2006). All of these threats may drive endemic and rare plant species to extinction risk.

R. arabica Crép. (Rosaceae) is a perennial prickly shrub 2–3 m tall (Fig. 1b). It is an exclusive endemic species to St. Catherine Protectorate. It is only restricted to mountain wadis and gorges habitats near moist grounds at high elevations (Moustafa et al., 2001, 2017). During our filed surveys, *R. arabica* was recorded in nine localities within St. Catherine: Wadi Elarbain, Kahf Elgholah, Shaq Mousa, Gebel Ahmar, Farsh Elrumanna, Wadi Saqr, Wadi Tinia, Gebel Catherine, and Wadi Abu Twitta. The population size of *R. arabica* was of 81 individuals distributed in the above-mentioned nine localities. The highest number of mature individuals was recorded in Wadi Abu Twitta (14 individuals). These results are almost completely in accordance with Omar (2017), who recorded 90 mature individuals in 14 localities in 2015, reporting a continuous declining in number and extent of occurrence of *R. arabica* in the last 10 years. For a long-term monitoring of *R. arabica*, three permanent fenced enclosures (Kahf Elgholah, Shaq Mousa and Monastery garden in Wadi Elarbain) were made in 1998 (Moustafa et al., 2017).

R. arabica is a medicinal plant rich in active phenolic metabolites in addition to its high pastoral importance (Moustafa et al., 2017; Souleman and El-Mousallamy, 2000). Its flower and fruits can be used to treat the pain of woman's during the menstrual period and also in the ethnoveterinary use. Its edible fruits are used by local Bedouins as well as cutting off its branches for grafting the garden roses (Abd El-Ghani and Fahmy, 1994; Omar, 2017). *R. arabica* is listed as one of the most rare and threatened species in Egypt (Abd El-Ghani and Fahmy, 1994; Moustafa et al., 2017) and also assessed as a critically endangered (CR) taxon with an Extent Of Occurrence (EOO) of 40 km^2 and an Area Of Occupancy (AOO) of 36 km^2 (Omar et al., 2017).

2.2. Data sources and variables selection

The current distribution data of *R. arabica* in the study area was collected from fieldwork after revision of literature (Abd El-Ghani and Fahmy, 1994; Ayyad et al., 2000; Danin et al., 1985; Moustafa and Klopatek, 1995; Moustafa et al., 2001, 2017; Omar et al., 2017; Täckholm, 1974). We dealt with the autocorrelation issues by eliminating redundant presences in each 1 × 1 km grid on the scale of the bioclimatic variables used (de Luis et al., 2018). Furthermore, records were screened in ArcGIS 10.4.1 for spatial autocorrelation using average nearest neighbour analyses to remove spatially correlated data points (Bosso et al., 2016; Smeraldo et al., 2018). After this selection, 32 occurrence points of *R. arabica* were used to generate SDMs (Fig. 1a).

Twenty-two variables were retrieved as predictors to model the potential environmental niche of *R. arabica* based on its current presence dataset. In particular, 19 bioclimatic layers and one topographic variable (elevation) were obtained from WorldClim database (http://www.worldclim.org/, Hijmans et al., 2005) at a spatial resolution of 30 arc-second (*ca.* 1 × 1 km). From elevation data, slope and aspect were extracted using ArcGIS 10.4.1. The overall environmental variables are summarized in Table 1. In order to eliminate multicollinearity and select the most fitting predictors that show more contribution power to the model, Variance Inflation Factors (VIFs) of 22 environmental variables were tested. VIFs are based on correlation coefficients (R^2) that

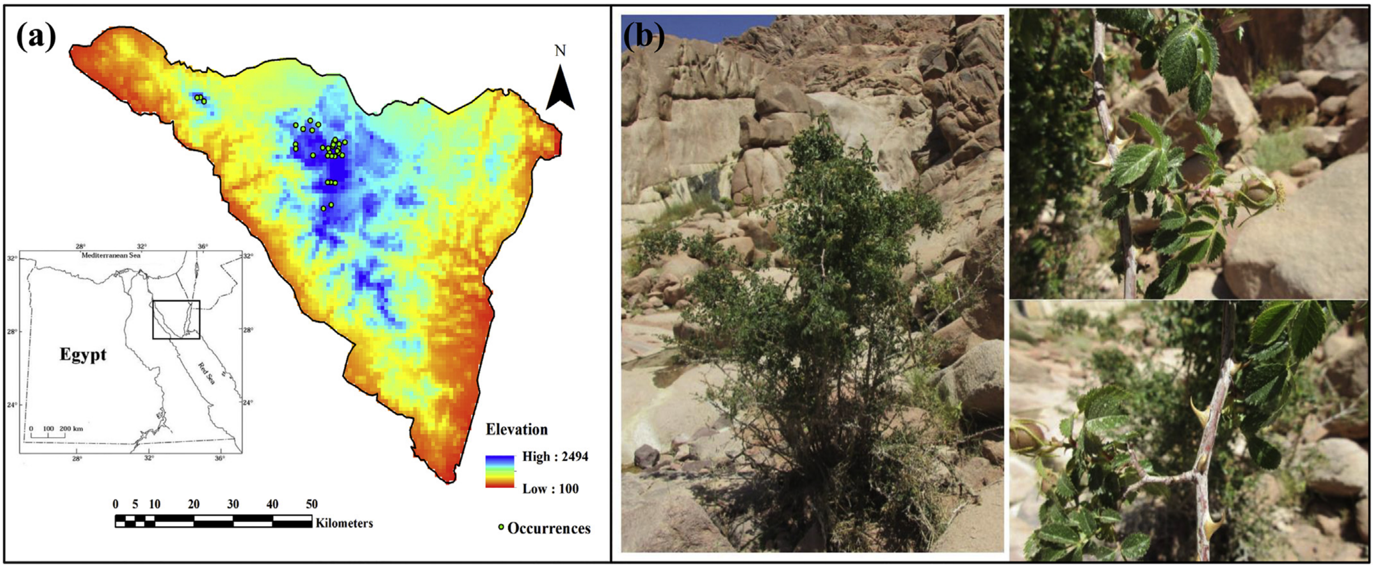

Fig. 1. (a) Map of Saint Catherine Protectorate with occurrence points of *Rosa arabica* and (b) *Rosa arabica* Crép.

Table 1
Environmental variables used for modeling the potential distribution of *R. arabica*. Problems related to collinearity were avoided by removing variables with variance inflation factor (VIF) values > 5. The highlighted variables were selected through multi-collinearity test and were used in modeling.

Variable	Code/Unit	Source	VIF
Annual mean temperature	**Bio1 (°C)**	**WorldClim**	**2.05**
Mean diurnal range (max. **Temp – min. temp)**	**Bio2 (°C)**	**WorldClim**	**3.68**
Isothermality (Bio2/Bio7) × 100	**Bio3**	**WorldClim**	**2.95**
Temperature seasonality (SD × 100)	Bio4 (°C)	WorldClim	14.71
Max temperature of warmest month	Bio5 (°C)	WorldClim	11.10
Min temperature of coldest month	Bio6 (°C)	WorldClim	8.56
Temperature annual range (Bio5-Bio6)	Bio7 (°C)	WorldClim	12.90
Mean temperature of wettest quarter	Bio8 (°C)	WorldClim	24.08
Mean temperature of driest quarter	**Bio9 (°C)**	**WorldClim**	**4.20**
Mean temperature of warmest quarter	Bio10 (°C)	WorldClim	14.55
Mean temperature of coldest quarter	Bio11 (°C)	WorldClim	18.21
Annual precipitation	**Bio12 (mm)**	**WorldClim**	**3.06**
Precipitation of wettest month	Bio13 (mm)	WorldClim	16.81
Precipitation of driest month	**Bio14 (mm)**	**WorldClim**	**3.29**
Precipitation seasonality (Coefficient of variation)	**Bio15**	**WorldClim**	**3.35**
Precipitation of wettest quarter	Bio16 (mm)	WorldClim	23.73
Precipitation of driest quarter	Bio17 (mm)	WorldClim	9.67
Precipitation of warmest quarter	Bio18 (mm)	WorldClim	11.14
Precipitation of coldest quarter	Bio19 (mm)	WorldClim	9.55
Elevation	**Elev (m)**	**WorldClim**	**3.56**
Slope	SL (%)	Derived from Elev	9.17
Aspect	AS (degrees)	Derived from Elev	10.80

Table 2
Estimates of average contribution and permutation importance of the environmental variables used in MaxEnt modeling of *R. arabica*.

Variable	Percent contribution	Permutation importance
Bio1	2.01	68.27
Bio2	1.06	1.34
Bio3	0.29	0.53
Bio9	0.12	0.34
Bio12	84.45	20.30
Bio14	0.05	0.01
Bio15	0.25	0.46
Elev	11.78	8.74

created from regression among all predictors and was implemented through the 'sdm' package in the R-environment (version 3.1.1). Consequently, 14 variables with VIFs > 5 were excluded (Chatterjee and Hadi, 2006) and only eight variables were kept to establish the distribution model of *R. arabica* under the current conditions (~1960–1990). The selected variables include annual mean temperature (Bio1), mean diurnal range (Bio2), isothermality (Bio3), mean temperature of driest quarter (Bio9), annual precipitation (Bio12), precipitation of driest month (Bio14), precipitation seasonality (coefficient of variation, Bio15) and elevation (Elev). Similarly, all of these non-linear variables with an exception of elevation were used for *R. arabica* modeling under future global warming scenarios. In the 5th report of the Intergovernmental Panel on Climate Change (IPCC, 2014), four representative concentration pathways (RCPs) were set using the total radioactive forcing of values 2.6, 4.5, 6 and 8.5 watt/m^2. Two of these scenarios, RCP2.6 (minimum emission hypothesis) and RCP8.5 (maximum emission hypothesis) were chosen in our study. One global climate model CCSM4 was obtained from WorldClim database under both scenarios over the periods 2050 (average for 2041–2060) and 2070 (average of 2061–2080). CCSM4 is one of the most efficient global climate projection that predicts the influence of future climatic changes on the distribution of plant species and was already successfully tested in similar environments (Al-Qaddi et al., 2017; Sanjerehei and Rundel, 2017).

2.3. MaxEnt model

In our study, all models were run using the MaxEnt algorithm (version 3.3.3 k; Phillips et al., 2006) with default settings. We employed 10 replicates and average of probability maps for habitat suitability (Hoveka et al., 2016). It is better to use MaxEnt model particularly when the data points include presence-only with a limited number of records (Bosso et al., 2013; Fois et al., 2015, 2018b; Vasconcelos et al., 2012). The training and test data points were 80% and 20%, respectively. The relative importance of each environmental predictor for the models of *R. arabica* was assessed using percent contribution of Jackknife test (Phillips et al., 2006), which is the best index for small sample sizes (Pearson et al., 2007). To determine the accuracy of the resulting models, we computed the Area Under the Curve (AUC) of the Receiver Operating characteristic Curve (ROC). AUC score is the dominant tool to measure the model performance, mainly due to its independence by threshold choices (Bosso et al., 2013; Fois et al., 2018b; Yi et al., 2016). The higher the value of AUC (closer to 1), the

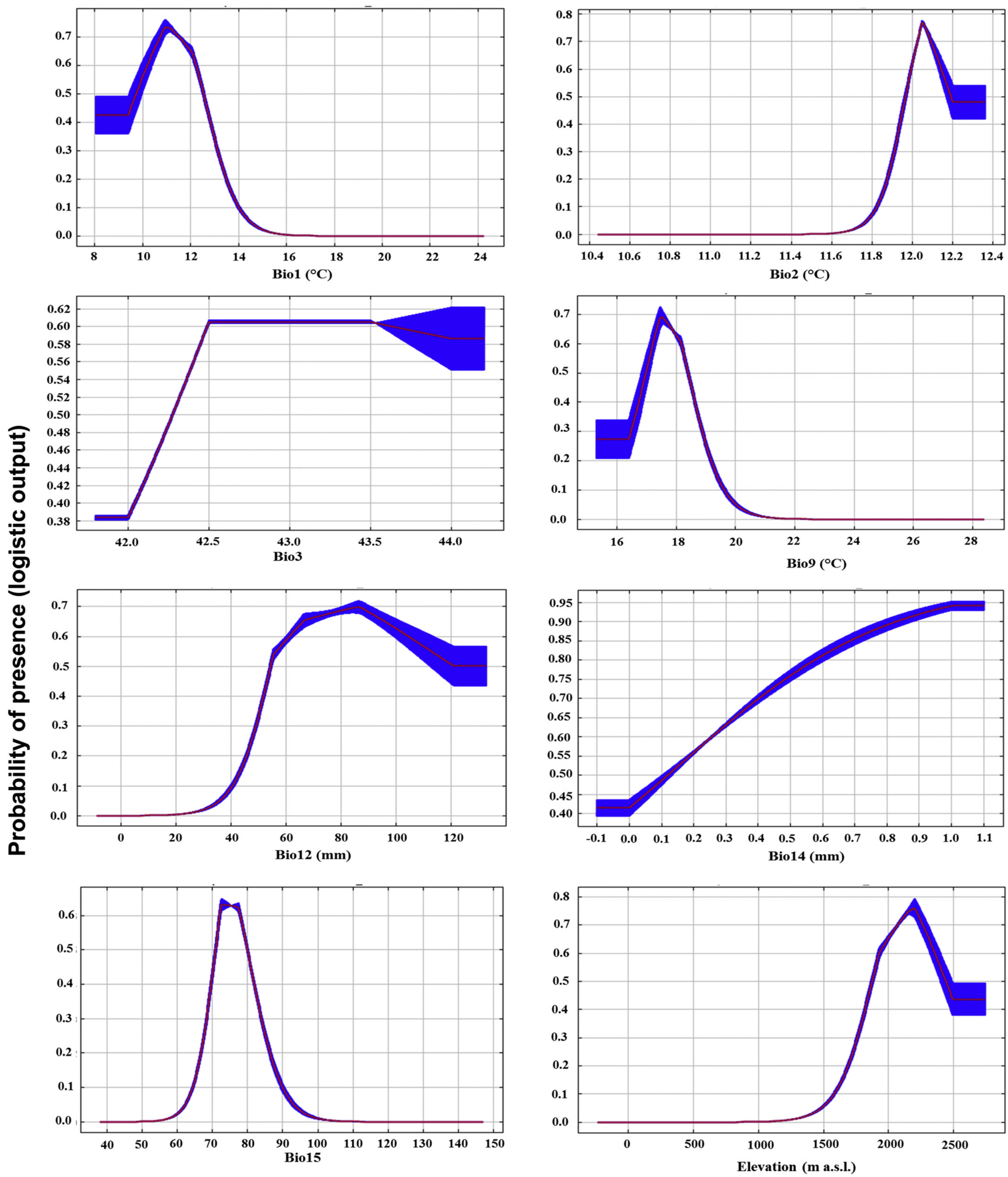

Fig. 2. Response curves of eight environmental predictors used in the ecological niche model for *R. arabica*. For abbreviations, see Table 1.

better the performance of the model (Fielding and Bell, 1997; Phillips et al., 2006). The generated AUC graph is obtained by plotting the true positive predictions (sensitivity) against the false positive predictions (1-specificity) (Fielding and Bell, 1997). In addition, the minimum difference between training and testing AUC data (AUC_{Diff}) was also considered; a smaller difference indicates lesser overfitting present in the model (Fois et al., 2018b; Warren and Seifert, 2011).

The logistic output of MaxEnt application is a map, indexing the environmental suitability of *R. arabica* with values ranging from 0 (unsuitable) to 1 (optimal). For further analysis, the MaxEnt results

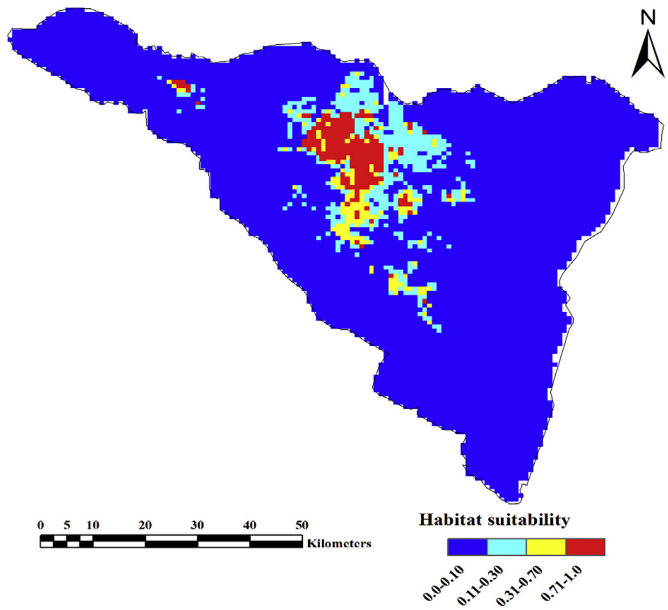

Fig. 3. Map for potential current habitat suitability of *R. arabica* according to occurrence records in St. Catherine. Habitat suitability classes include: unsuitable (0 – 10), low potential (0.11–0.30), moderate potential (0.31–0.70) and high potential (0.71–1.0).

were imported into ArcGIS 10.4.1, and four classes of potential habitats were grouped as follows: unsuitable (≤0.10), low potential (0.11–0.30), moderate potential (0.31–0.70) and high potential (≥0.71) (Choudhury et al., 2016; Qin et al., 2017; Yang et al., 2013). Changes in the predicted ecological extent of *R. arabica* between the current and future climatic scenarios in correspondence of classes were computed as follows: MaxEnt ASCII output projections were converted to raster layers with float data-type using ArcGIS 10.4.1, then the number of cells (pixels) among projected climatic extent was calculated using zonal statistics in spatial analyst tools in ArcGIS 10.4.1. The differences in the mean number of cells among four classes of potential habitats were converted to surface area (km^2) (Fielding and Bell, 1997). Finally, the predictive maps of MaxEnt for the current and future scenarios were related with elevation classes.

3. Results

3.1. Potential habitat suitability of R. arabica over current conditions

Our models showed high levels of predictive performances with values of AUC (training, 0.985 ± 0.001; test, 0.968 ± 0.009) and AUC_{Diff} (0.010 ± 0.007). The results of variables' contribution using Jackknife test in distribution modeling of *R. arabica* are showed in Table (2). Environmental predictors that exhibited the highest mean contributions were annual precipitation (Bio12), elevation (Elev) and annual mean temperature (Bio1). Bio12, Bio1, Bio9, Elev and Bio2 provided high gains (> 2) to the model when used individually, indicating that these variables have the most useful information by themselves than the rest of variables. Considering permutation importance, Bio1, Bio12 and Elev were the main environmental variables which have influenced the potential distribution of *R. arabica* (Table 2).

The response curves of eight variables to *R. arabica* habitat suitability are shown in Fig. 2. While considering probabilities of temperature variables, the mean annual temperature range (Bio1) of *R. arabica* was 8.05–15.4 °C, whereas the mean diurnal temperature (Bio2) ranged from 11.7 °C to 12.2 °C. In addition, the range of isothermality (Bio3) varied from 42 to 44.2, whereas the mean temperature of driest quarter (Bio9, three driest months) varied from 15.3 to 20 °C. On the other hand, the range of annual precipitation (Bio12) was 36 to 120 mm per year while the suitable habitat occurs also when the precipitation seasonality of 58 to 97.5 with a peak for *R. arabica* at 72.5 mm. Furthermore, there is a positive relationship between habitat suitability of *R. arabica* and precipitation of the driest month. The suitable elevation range of *R. arabica* was 1571 to 2273 m with an optimal elevation at around 2200 m a.s.l. Indeed, the highest suitability under which presence of *R. arabica* occurs resulted at an annual temperature of 10.9 °C, 87.50 mm annual precipitation, and an elevation of 2200 m a.s.l. In contrary, areas with an elevation higher than 2300 m a.s.l. or lower than 1500 m a.s.l, and with an annual temperature higher than 20 °C were the less suitable for *R. arabica*.

The potential distribution map of *R. arabica* in St. Catherine is displayed in Fig. 3. Out of 5196 km^2 of the total area, 4627 km^2 (≤0.10) was unsuitable for *R. arabica*; the remaining 596 km^2 was divided into 282 km^2 with a low potential distribution, 247 km^2 with a moderate potential and only 40 km^2 with the highest probability of suitable ecological conditions. The majority of suitable habitats (≥0.71) was located in the middle northern part of St. Catherine area.

3.2. Distribution of suitable habitats of R. arabica under future global warming scenarios

The projected climate map under CCSM4 model for both 2050 and 2070 resulted in a progressive reduction of the extent of suitable habitat for *R. arabica*, as compared with the potential current distribution (Fig. 4 and Table 3). At both minimum and maximum emissions scenarios (RCP2.6 and RCP8.5, respectively), the habitat suitability decreased with climate warming. By 2050, the potential unsuitable areas for *R. arabica* (≤0.10) within St. Catherine would increase by 0.26% and 0.37% due to rising of global warming from 2.6 watts/km^2 to 8.5 watts/km^2. A similar pattern was also confirmed in 2070 by gain percentages of 0.45% and 1.19%, respectively. By focusing on the moderate potential occurrence (0.31–0.70), there were gains in the areas suitable for *R. arabica* at both climatic future scenarios. In contrast, at high potential distribution class (≥0.71) and by 2050, the habitat suitability will decrease by 47.5% and 60% for RCP2.6 and RCP8.5, respectively. For 2070, the climate change may lead to losses of 60% and 72.5% in *R. arabica* current habitat under RCP2.6 and RCP8.5, respectively. Compared with the current potential distribution, a gradual range contraction is observed in the northwestern and southern parts of St. Catherine under predicted climate change. Comparing predictive maps with elevation classes indicated that *R. arabica* would disappear in sites located below 1500 m a.s.l., contract between 1500 and 2000 m a.s.l. and expand its range towards sites located between 2000 and 2500 m a.s.l. during future projections (Fig. 5).

4. Discussion

Our results showed that, under the current climatic condition, the environmental suitability of *R. arabica* lies within the middle northern boundaries of St. Catherine. This finding fits with our field observations and the known distribution reported in literature (Täckholm, 1974; Danin et al., 1985; Abd El-Ghani and Fahmy, 1994; Moustafa et al., 1995; Ayyad et al., 2000; Moustafa et al., 2001, 2017; Omar et al., 2017), and suggests that the current distribution represents its climate optimum at sites with high altitude and near fresh water springs.

Models' results also displayed some topographic-climatically suitable sites within St. Catherine such as Gebel Musa, Mountain Tarboush, Wadi Jibal, Mountain Serbal, Zaater, Elmaeen, Sad Abu Hebeik and Kharazet Elshak where no historic or literature data provide an evidence for the occurrence of this plant before, except for the last four sites where *R. arabica* has been recorded by St. Catherine rangers in 2015 (Omar et al., 2017) and subsequently not found during our field surveys. Such possible local extinctions (Zaater, Sad Abu Hebeik, Kharazet Elshak, Elmaeen,) are at the altitudes of 2100, 2000, 1940,

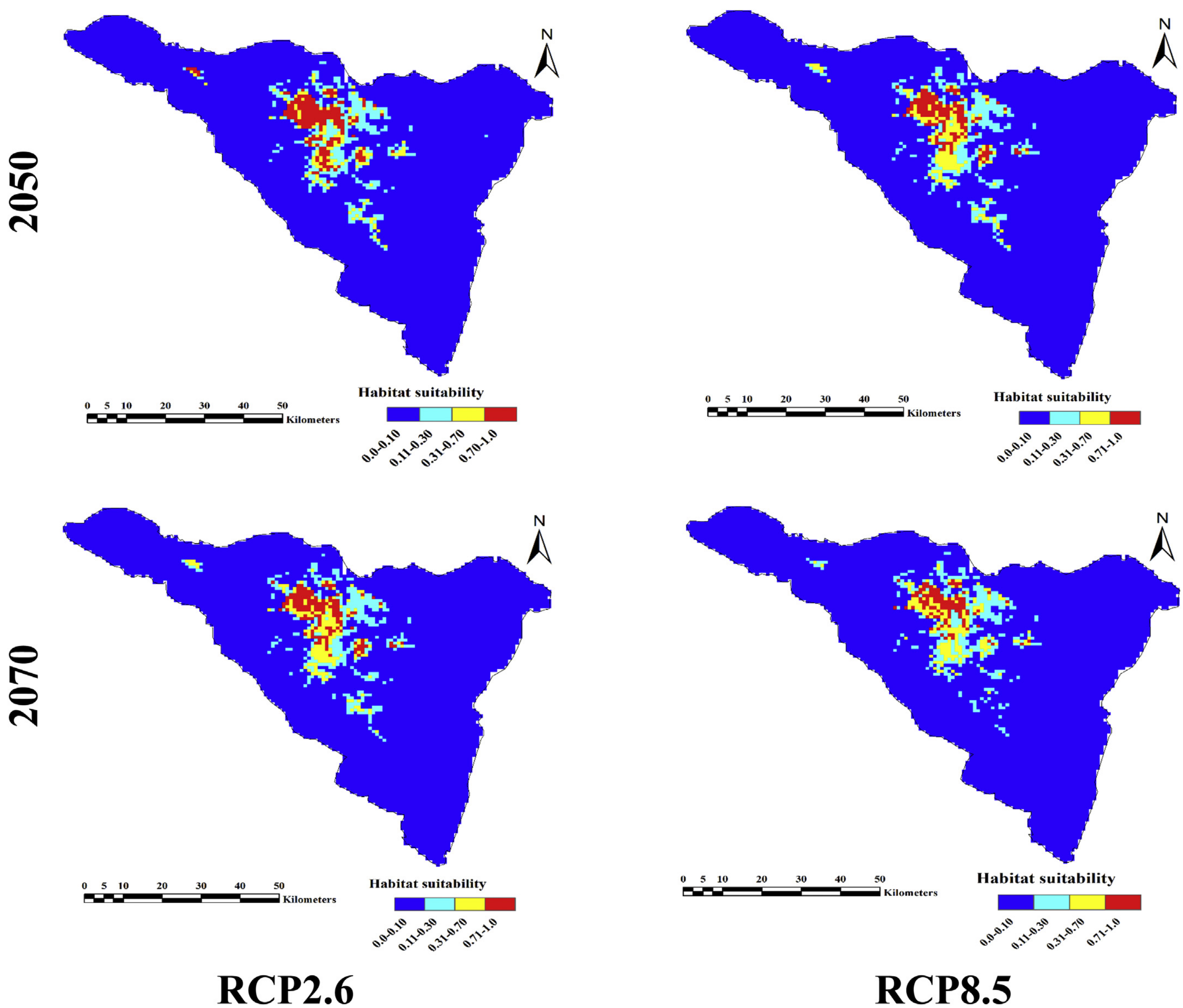

Fig. 4. Ecological niche modeling of *R. arabica* based on predicted climate change for 2050 and 2070 at two global warming scenarios RCP2.6 and RCP8.5. Habitat suitability classes include: unsuitable (0–10), low potential (0.11–0.30), moderate potential (0.31–0.70) and high potential (0.71–1.0).

Table 3
Predicted range changes (km^2) for *R. arabica* distribution for 2050 and 2070 at two global warming scenarios RCP2.6 and RCP8.5 as compared with the potential current distribution. In brackets (+) gain and (−) loss range areas (in km^2).

Predicted class	Current	Future scenarios			
		2050		2070	
		RCP2.6	RCP8.5	RCP2.6	RCP8.5
0.0–0.10 Unsuitable	4627	4639 (+12)	4644 (+17)	4648 (+21)	4682 (+55)
0.11–0.30 Low potential	282	276 (−12)	246 (−36)	232 (−50)	208 (−74)
0.31–0.70 Moderate potential	247	262 (+16)	290 (+43)	302 (+55)	295 (+48)
0.71–1.0 High potential	40	19 (−21)	16 (−24)	14 (−26)	11 (−29)

1795 m a.s.l., respectively. These recent local extinctions occurred in suitable sites where the plant was previously present with very small population size, therefore, reasons may be attributed to stochastic events or human disturbances (overgrazing and excessive collection). Nonetheless, further surveys efforts are encouraged in such sites for the search of new *R. arabica* populations or to investigate which factors have contributed to preventing the colonization of this species in all suitable places.

All of the current and predicted sites fulfill the *R. arabica* requirements where high elevation (1500–2273 m a.s.l.), cold temperature (8.05–15.4 °C) and annual precipitation range of 36–120 mm. Consequently, warm sites with elevation < 1500 m a.s.l are less suitable for *R. arabica*. These results are in line with Moustafa and Kamel (1995) who reported that *R. arabica* mainly occurs in moist gorges habitats with a narrow elevation range from 2000 to 2400 m a.s.l. at mountain peaks.

In addition, MaxEnt outputs under current conditions indicated that *R. arabica* distribution range was more influenced by annual temperature, annual precipitation and elevation. This is consistent with factors affecting the suitable habitats of several medicinal and endangered

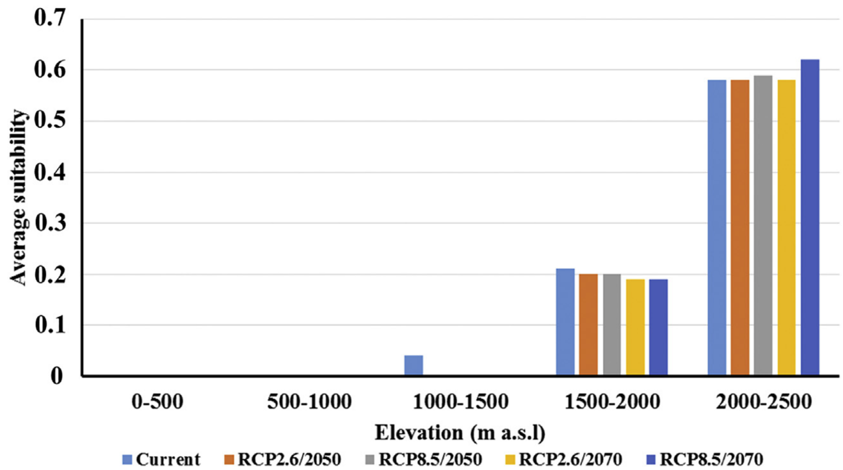

Fig. 5. Average habitat suitability of *R. arabica* in relation to elevation range classes under current and future climate change scenarios.

mountain plant species such as *Myristica dactyloides* (Remya et al., 2015), *Fritillaria cirrhosa* (Zhao et al., 2018), *Quercus coccifera* (Al-Qaddi et al., 2017), *Gentiana lutea* (Cuena-Lombraña et al., 2018), *Artemisia* spp. (Sanjerehei and Rundel, 2017) and *Daphne mucronata* (Abolmaali et al., 2018), where climatic factors and elevation resulted the most crucial drivers in plant species' distribution. Also in Egypt, the importance of climatic factors and elevation was confirmed for the spatial distribution of medicinal plants (Kaky and Gilbert, 2016), and for the distribution of *Hypericum sinaicum* and *Nepeta septemcrenata* in St. Catherine Protectorate (Khafagi et al., 2011, 2012). More in general, the distribution of endemic taxa within St. Catherine is largely driven by rainfalls and elevation (Moustafa et al., 2001).

MaxEnt predictions for the years 2050 and 2070 disclosed that the geographic distribution of *R. arabica* would shrink under the future conditions. The projected models showed habitat range shifts through the disappearance of this species in sites below 1500 m a.s.l., range contraction at 1500–2000 m a.s.l. and range expansions towards optimum environmental conditions at higher elevation sites (2000–2500 m a.s.l.). The reason of range shift is that the climatic envelope (precipitation and temperature) of this plant will become less suitable for survival at sites below 2000 m a.s.l.; such phenomenon was also reported for other mountain plant species in northern Africa (Al-Qaddi et al., 2017), Middle East (Abolmaali et al., 2018; Khanum et al., 2013) and in the Mediterranean mountains (Fois et al., 2016; López-Tirado et al., 2018). Nonetheless, low survival and germination rates at high temperatures were observed after *ex situ* experiments (El-Demerdash, 2007) and further studies should consider these limitations at the time of estimating the future conservation status of this plant.

Plants differ in their responses against future climate change which depend mainly on their physiological or phenological characteristics (Zhao et al., 2018). Particularly, plants with wide ecological niches will be more able to adapt to climate change than species with narrow ecological niches (Abolmaali et al., 2018; Khanum et al., 2013). For instance, significant improvement in habitat suitability with global warming for *Homonoia riparia* in China (Yi et al., 2016) and for *Ruscus aculeatus* in Sardinia (Fois et al., 2018a). In contrast, a considerable reduction in suitable habitats for many other species, such as *Myristica dactyloides* in India (Remya et al., 2015), *Fritillaria cirrhosa* in China (Zhao et al., 2018), *Artemisia aucheri*, *A. sieberi* and *Daphne mucronata* in Iran (Abolmaali et al., 2018; Sanjerehei and Rundel, 2017) was predicted for future climate change. In both cases, range shifts, more than retractions, were the crucial information to be considered when efficient conservation measures are planned (Fois et al., 2018a; Koch et al., 2017).

In the case of *R. arabica*, a species with a narrow geographical niche and dispersal ability may particularly reduce the ability of this plant to face global climate change consequences, especially if human-induced habitat fragmentation increases barriers to dispersal.

5. Conclusion

This study indicated that the geographic distribution of *R. arabica* might undergo habitat range shifts through the disappearance of this species in sites below 1500 m a.s.l., range contraction between 1500 and 2000 m a.s.l. and range expansions towards optimum habitats at sites with higher elevation (2000–2500 m a.s.l.). Moreover, as a high-altitude plant sensitive to high temperature, *R. arabica* cannot withstand the future global warming. In order to reduce the risk of extinction in the wild, *ex situ* and *in situ* conservation measures for *R. arabica* are urgent. Specifically, reinforcements of the existing populations, as well as programs of assisted migrations should be planned in the wild. These activities should be accompanied by an increase of public awareness and policy activities with the aim of reducing impacts related to human activities.

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